Explore QCD phase transition with thermal photons

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Abstract This pilot study was to assess the high temperature and zero baryon density region of quantum chromodynamics (QCD) phase diagram with thermal photon emission, where the nature of QCD phase transition is ambiguous. Based on a (3+1)-D ideal hydrodynamical model to describe macroscopically the collision system, thermal photons emitted from Pb+Pb collisions at 2.76 TeV are investigated. The result reveals that photons from heavy ion collisions at high energy and centrality are possible to distinguish the structure of the hot dense matter, in QGP phase or hadronic phase, thus may provide an approach to explore the nature of this finite-temperature QCD transition (that is, first-order, second-order or analytic crossover).

Key words Phase diagram, Hydrodynamical model, Photon emission rate

1 Introduction

Quantum chromodynamics (QCD) is the theory of the strong interaction, explaining (for example) the binding of three almost massless quarks into a much heavier proton or neutron. The standard model of particle physics predicts a QCD-related transition. At low temperatures, the dominant degrees of freedom are colorless bound states of hadrons (such as protons and pions). Because of asymptotically free, at high energies or temperatures, hadrons break up into quark degrees of freedom. Despite enormous theoretical efforts, the nature of this finite-temperature QCD transition (that is, first-order, second-order or analytic crossover) remains ambiguous. Here we explore the nature of the QCD transition with thermal photon emission in heavy ion collisions.

Photon emission rates from different phases, hadronic gas and quark gluon plasma, are investigated. According to Kapusta's pioneer investigation[1,2], the conclusion is that photon emission rates from the two different phases are comparable at temperature around 200 MeV. However, in QCD phase diagram, the temperature involving the finite-temperature QCD transition has a quite wide range, from T_c ~170 MeV to a few times of T_c. Therefore photon emission rates from two phases at temperate ranged from 200 MeV to much higher temperature, i.e., 700 MeV, have been investigated. On one hand, it is hard to accept the existence of hadron gas at temperate higher than T_c. On the other hand, the matter situation is not a pure QGP phase according to the most popular lattice results, a cross-over phase transition. Therefore, we still consider the part other than QGP matter as a hadronic matter and take photon emission rate from hadronic gas to estimate the unknown emission rate.

The temperature-dependent photon emission rate study tells that at very high temperature, the photon emission rates from different phases differ from each other with a factor of several magnitudes. This will make a clear identification of the nature of this finite-temperature QCD transition possible.

However, one needs a real measurement based on a certain experiment to distinguish the different options of this finite-temperature QCD transition. Therefore, a high temperature matter should be created, and the photon emission should be measured. The best choice is Pb+Pb collisions at 2.76 TeV, which makes the existence of high temperature matter possible. Then based on a (3+1)-D ideal hydrodynamical model to describe macroscopically the collision system,

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thermal photons emitted from Pb+Pb collisions at LHC energy 2.76 TeV with two options phase transitions are investigated.

2 Approach and results

In this section we will introduce our approach in detail. Here we need several segments of this study. We introduce them one by one in the following.

2.1 Thermal photon emission rates

Thermal photon production is obtained by integrating the photon emission rate *R* (number of reactions per unit time per unit volume which produce a photon) over the space-time history of the expanding hot and dense matter. In this section we study the photon emission rates from different phases of the hot dense matter.

The spectral photon emissivity directly reflects the dynamics of real photon production reactions in thermalized matter. Commonly employed formalisms are finite-temperature field theory and kinetic theory. As systematically studied by Kapusta *et al.*[1,2], the thermal emission rate of photons with energy *E* and momentum $\vec{p}$ from a small system (compared to the photon's mean free path) is

$$E\frac{dR}{d^3p}=\frac{-2}{(2\pi)^3}\mathrm{Im}\Pi_\mu^{R,\mu}\frac{1}{\exp(E/T)-1}, \tag{1}$$

where $\Pi_\mu^{R,\mu}$ is the retarded photon self-energy at finite temperature *T*. This formula has been derived both perturbatively and nonperturbatively. It is valid to all orders in the strong interaction. If the photon self-energy is approximated by carrying out a loop expansion to some finite order, then the formulation of Eq.(1) is equivalent to relativistic kinetic theory, where the emission rate of photons with energy *E* and momentum $\vec{p}$ from a process of type $1+2\to3+\gamma$ reads as

$$\begin{aligned}E\frac{dR}{d^3p}=&\int\left(\prod_{i=1}^{3}\frac{d^3p_i}{(2\pi)^3 2E_i}\right)(2\pi)^4\\&\times\delta^{(4)}(p_1^\mu+p_2^\mu-p_3^\mu-p_\gamma^\mu)\\&\times|M|^2\frac{f_1(E_1)f_2(E_2)[1\pm f_3(E_3)]}{2(2\pi)^3},\end{aligned} \tag{2}$$

where *f*'s are the Fermi-Dirac or Bose-Einstein distribution functions as appropriate. Eq.(2) is convenient if the scattering amplitude, *M*, is evaluated in a perturbative expansion. Non-perturbative (model) calculations at low and intermediate energies, on the other hand, are more amenable to the correlator formulation, Eq.(1). In the hadronic medium, e.g., Π_{em} can be directly related to vector meson spectral functions within the vector dominance model (VDM). Instructive investigation on photon emission rates from both QGP and HG phases can be found in Refs.[1,2].

The thermal rate from a quark-gluon plasma is computed using the kinetic theory formalism for the simplest two-to-two scattering diagrams such as the QCD Compton process $qg\to\gamma q$ and annihilation $q\bar{q}\to g\gamma$[1,2]. As noted in Ref.[3], this does not yet comprise the full result to leading order in the strong coupling constant α_s. Due to collinear singularities, bremsstrahlung as well as pair annihilation graphs contribute at the same order as the resumed $2\to2$ processes. The full result, which also necessitates the incorporation of Landau-Pomeranchuk-Migdal (LPM) interference effects, has been computed in Ref.[4,5] as

$$\begin{aligned}E\frac{dR^{\mathrm{QGP}\to\gamma}}{d^3p}=&\sum_{i=1}^{n_f}\left(\frac{e_i}{e}\right)^2\frac{\alpha\alpha_s}{2\pi^2}T^2\frac{1}{e^x+1}\\&\times\left[\ln\left(\frac{\sqrt{3}}{8}\right)+\frac{1}{2}\ln(2x)+C_{22}(x)+C_{\mathrm{brems}}(x)+C_{\mathrm{ann}}(x)\right]\end{aligned} \tag{3}$$

with convenient parameterizations of the three functions *C*. The corresponding results at different temperatures are illustrated in Fig.1 as solid lines.

Photons can also be produced in a hadronic phase, from several elementary interactions. The dominant contribution[1,2] comes from the reactions $\pi\pi\to\rho\gamma$ and $\pi\rho\to\pi\gamma$. The decay $\rho\to\pi+\pi+\gamma$ also contributes significantly. Interactions involving strange mesons or baryons can also produce photons, but these contributions are relatively small because of the phase-space suppression due to their big masses.

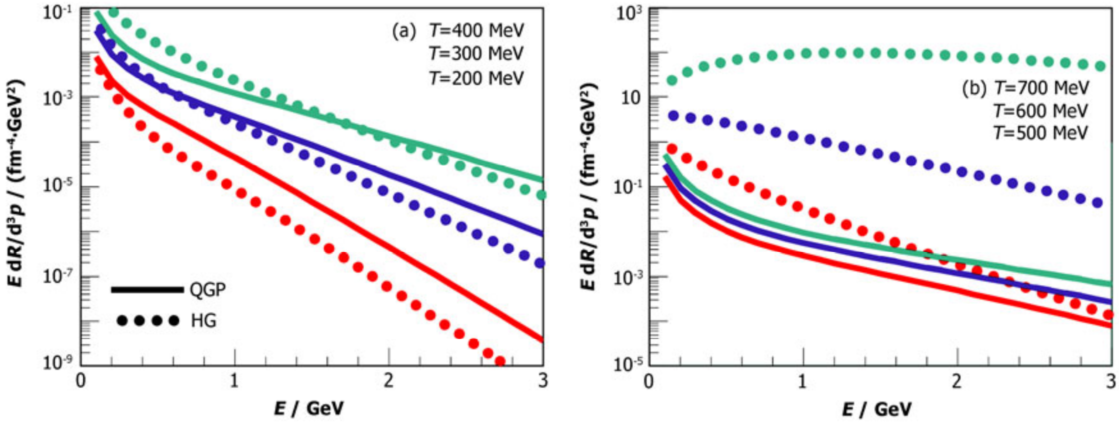

Fig.1 (Color online) Photon emission rates at temperatures T=200 MeV, 300 MeV, ···, 700 MeV from QGP phase (solid lines) and hadronic phase (dotted lines).

The situation of thermal photon radiation rates from a hadronic gas is uncertain, due to difficulties related to the strong coupling and the masses of hadrons. The study is usually carried out within effective Lagrangians. Constraints on the interaction vertices can, to a certain extent, be imposed by symmetry principles (e.g., e.m. gauge and chiral invariance). Coupling constants are estimated by adjusting to measured decay branchings in the vacuum. Thus, for the temperature ranges relevant to practical applications, the predicted emission rates are inevitably beset with significant uncertainties, and therefore a careful judgment of the latter becomes mandatory. We will use the results of the MYM calculation[6] and plot the corresponding parameterized rates in Fig.1 as dotted lines.

We can see that at temperature below 500 MeV, the emission rates from the two different phases are comparable. But the temperature reaches 600 MeV or even higher, the emission rate from hadronic gas is several magnitudes higher than the rate from QGP phase. This makes possible an identification of what is the matter at the relevant region of the QCD phase diagram, thus to tell the order of phase transition.

2.2 Evolution of a heavy ion collision system

The expanding local-thermalized matter created in heavy-ion collisions, is treated by employing three-dimensional hydrodynamics[7], *via* the flow velocity u, the energy density ε, pressure P, the entropy density s and the baryon number density n_B as functions of the space-time position (η, τ, r, φ), with η being the space-time rapidity, and r, φ being the transverse coordinates. Those quantities are governed with a hydrodynamical equation:

$$\partial_\mu T^{\mu\nu} = 0, \tag{4}$$

where energy-momentum tensor can be decomposed as $T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$ in ideal hydrodynamics. This hydrodynamical equation describes the collective motion of the collision system from an initial time until a freeze-out condition.

An event generator EPOS has been used to construct the initial condition. Additionally, a dynamical equation, i.e., the relation between energy density and the pressure is needed to close the hydrodynamical equation. The equation of state used is Ref.[8]. For more details of the solution of hydro equation, one can read Ref.[7]. In Fig.2, the resulted energy density at the initial time τ_0=0.35 fm/c from Pb+Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV at centrality 0%–40% (Fig.2a) and 40%–80% (Fig.2b) are shown. In this model, centrality is defined with impact parameter b, and constrained with experimental data such as rapidity distribution of produced hadrons and multiplicity distribution function. It is equivalent to the definition based on Glauber model. Here the impact parameter is $b \in [0, 9.85)$ and $[9.85, 13.93)$ fm for 0%–40% and 40%–80%, respectively. One can see more energy has been deposited in the midrapidity region to form the hot dense matter in more central collisions.

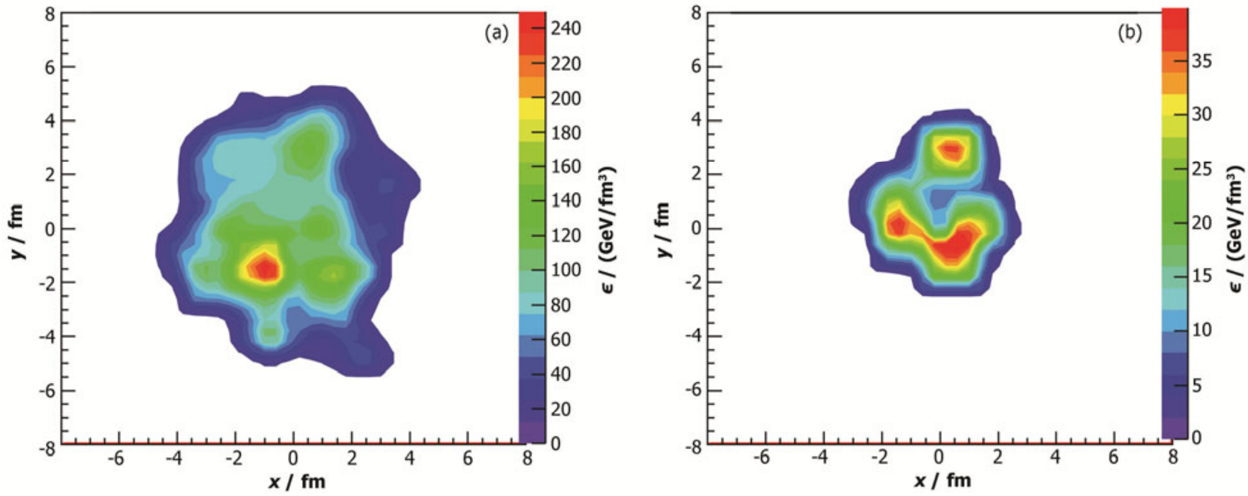

Fig.2 (Color online) Obtained energy density for Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV at the initial time τ_0=0.35 fm/c, centrality 0%–40% (a) and 40%–80% (b).

To calculate particle production, another equation of state, i.e., the relation between energy density and temperature is needed. For hadron production, this relation is only used at the Freeze-out condition. But for thermal photon emission, this relation is used through the whole hydrodynamical evolution. The relation between energy density and temperature is obtained based on the structure of the hot dense matter, i.e., a QGP or a hadronic gas, or anything. In this work, we still take the relation between energy density and temperature from lattice calculation[9]. The obtained temperature for Pb+Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV at the initial time τ_0=0.35 fm/c is shown at Fig.3 for centrality 0%–40% and 40%–80% respectively. We can see temperature as higher as 900 MeV has been reached in 0%–40% centrality, however, only in a small volume and for a short time interval. At most space-time points, the temperature will be lower than this peak value.

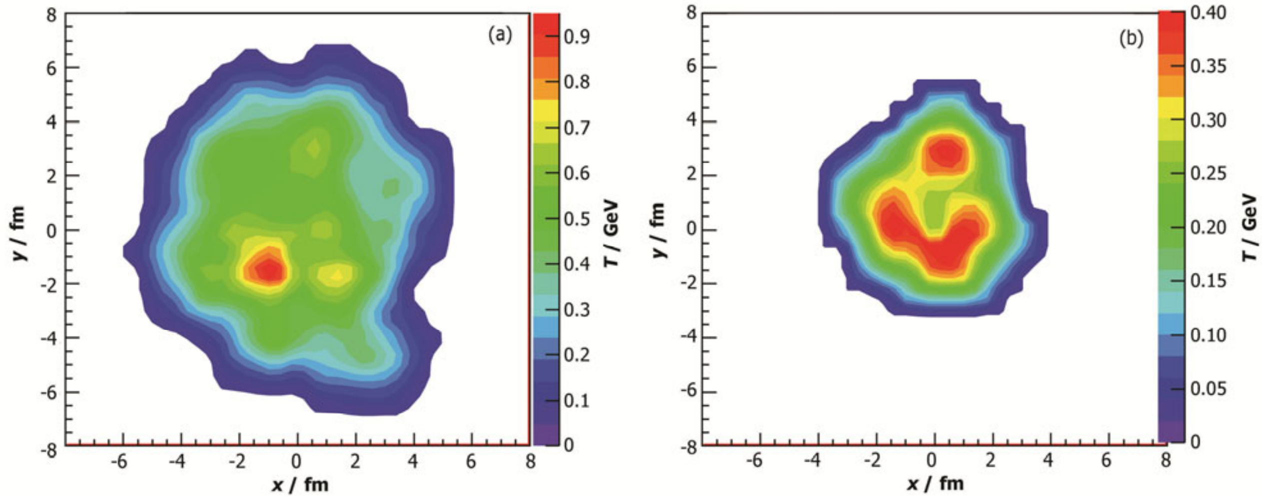

Fig.3 (Color online) Obtained temperature for Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV at the initial time τ_0=0.35 fm/c, centrality 0%–40% (a) and 40%–80% (b).

2.3 Thermal photon production

Thermal photon production is obtained by integrating the photon emission rate R (number of reactions per unit time per unit volume which produce a photon) over the space-time history of the expanding hot and dense matter:

$$\frac{dN}{dyd^2p_t}=\int d^4xR(p^\mu u_\mu,T), \tag{5}$$

where p^μ is the four-momentum of produced photon. The flow velocity u^μ and the temperature T are based on the above calculation. The photon emission rate covers emission from both QGP phase

and hadronic gas,

$$R = f_{\rm QGP} \cdot R^{\rm QGP\to\gamma} + (1 - f_{\rm QGP}) \cdot R^{\rm HG\to\gamma}, \quad (6)$$

where $f_{\rm QGP} = f_{\rm QGP}(x)$ is the fraction of QGP phase at a given space-time point.

There are two options of $f_{\rm QGP}$. Option one (opt1) is consistent with the dynamical equation of state, the equation of state from lattice QCD[8], where pressure is calculated[9] as $P = P_Q + \lambda(P_Q - P_H)$, one obtained the temperature-dependent $f_{\rm QGP} = 1 - \lambda$. This makes hadronic gas appear at very high temperature, with very small fraction, *ie*, about 4% at 700 MeV.

Option two (opt2) of $f_{\rm QGP}$ is defined according to first order phase transition, which was widely used in Ref.[9], where no fraction of hadronic gas appears at temperature higher than 200 MeV.

Due to the two options of $f_{\rm QGP}$, the transverse momentum spectra of thermal photons at midrapidity from Pb+Pb collisions at 2.76 TeV are plotted in Fig.4 for centrality 0%–40% (Fig.4a) and 40%–80% (Fig.4b). Dotted lines are results based on option one of $f_{\rm QGP}$. Solid lines are based on option two. At a later time, the system temperature gets cold and the emission of the two options is expected comparable due to the emission rates from the two different phases. Thus photons emitted at time later than τ_0=0.35 fm/*c* are counted as a comparison, i.e., from 0.75 fm/*c*, 1.15 fm/*c* and 1.55 fm/*c*, plotted as different dots and colors of lines.

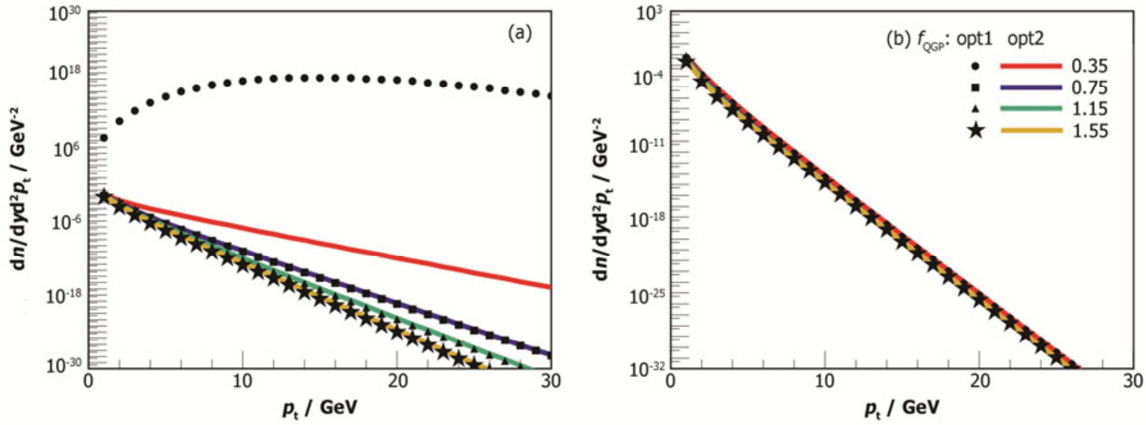

Fig.4 (Color online) Transverse momentum spectra of thermal photons at midrapidity from Pb+Pb collisions at 2.76 TeV.

3 Conclusion

The comparison of the transverse spectrum of thermal photons from Pb+Pb collisions at 2.76 TeV reveals that high collision energy and centrality are needed to create high temperature matter. And the early evolution is the most sensitive stage to distinguish the structure of the hot dense matter, in QGP phase or hadronic phase, thus may provide an approach to explore the nature of this finite-temperature QCD transition (that is, first-order, second-order or analytic crossover).

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